Training-induced change of tendon and muscle stiffness of the lower limb in professional female athletes: Assessment with shear wave elastography

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Abstract

Background:

Shear Wave Elastography (SWE) is currently used to detect tissue pathologies. For preventive medicine, it may also be applied to uncover structural changes early on before they lead to functional impairment. Hence, it is important to examine the sensitivity of SWE and to investigate how stiffness measures are affected by methodological variables.

Objective:

To evaluate the acute effects of exercise activity on tendon and muscle stiffness measured by SWE.

Methods:

Standardized SWE examination of both lower limb tendon and muscles (achilles tendon (AT), Musculus soleus insertion (MS) and Musculus gastrocnemius (MG)) in longitudinal plane were performed in 24 healthy professional female athletes. Measurements were taken before and after a standardized treadmill exercise test. Baseline characteristics and parameters of performance were acquired.

Results:

In the overall cohort, baseline SWE assessment demonstrated a moderate to strong correlation between pre-exercise and post-exercise stiffness for MS ($r=0.613$), MG ($r=0.609$) and AT ($r=0.583$). In both muscles (Musculus soleus insertion and Musculus gastrocnemius) and achilles tendon, the linear regression shows an increase in stiffness for lower pre-exercise values and decreasing stiffness for higher pre-exercise values. This covariance between pre-exercise values and changes in stiffness is highly significant ($p<0.001$).

Conclusion:

SWE measurement revealed that in professional athletes acute exercise induces individually different tissue stiffness changes. Differences and changes of stiffness in professional athletes after acute exercise needed to be considered for diagnosing tendinopathy and injuries. More precise and comparable research protocols in MSK-SWE may be of great benefit for sports medicine but also for rehabilitation and preventive medicine.

Introduction

As a result of the ongoing technical improvement, ultrasound (US) became more important in functional musculoskeletal (MSK) imaging. Moreover, applications such as Shear Wave Elastography (SWE) or microflow imaging add a quantitative evaluation of muscle or tendon tissue and therefore introduce multiparametric US (mpUS) in MSK imaging (1-3). SWE is based on measurements of shear wave speed

(SWS) and showed potential value in diagnosis of injuries and especially in discriminating tendinopathies with intra-individual changes compared to contralateral healthy tendons (4-6). The propagation speed of the shear waves in the tissue can be detected directly as a shear wave speed in the unit m/s, with a high speed for stiff and low speed for soft tissue (7, 8), and can thus be used as surrogate for tissue stiffness in form of a quantitative parameter (9). In addition, it can be safely applied to investigate both healthy as well as injured tendons and muscles, as no movement of the joint is required to detect elasticity. This allows easy and fast assessment of tissue stiffness in both muscles and tendons.

Since the shear wave velocity can be determined for small regions, shear wave elastography offers the possibility to compare specific areas within one tendon. This could be useful, for example, in the diagnosis of local pathological tissue changes such as tendinopathies Dirrichs et al. examined the application of shear wave elastography for the diagnosis of tendinopathies of the achilles and patellar tendon (10). Indeed, shear wave elastography, compared to B-mode and Power Doppler, showed a significantly lower rate of false-positive results and correlated stronger with clinical symptoms (10).

It is already known, that exercise activity in general and endurance training in particular affect the SWS (11, 12). An examination of achilles tendon showed higher SWE values in recreationally active subjects in comparison to non-active subjects (12). In addition, SWS has been shown to be sensitive to acute changes in muscle stiffness during muscle contraction ((9, 13). As tendon stiffness values may vary in relation to exercise activity, it is necessary to examine the acute effect of exercise in professional athletes. This will foster our understanding of tissue stiffness changes in this subgroup, which is needed to be able to develop diagnostic approaches in preventive medicine

Objective

The aim of this study was to evaluate the potential change in tendon and muscle stiffness before and after a standardized treadmill exercise in professional athletes. Standardized SWE examination of both lower limb tendon and muscles stiffness in longitudinal plane and relaxed tendon position were performed in 24 healthy professional female athletes.

Methods

Study cohort

The prospective study included 24 healthy professional female athletes, which were examined from June until August 2021. Inclusion criteria were I) age ≥18 years, II) healthy female professional athletes, III) without any acute (> 6 months) musculoskeletal, rheumatic or vascular comorbidities and no previous injuries of the achilles tendon, and IV) written informed consent to participate in the study. The study was conducted in accordance with the Declaration of Helsinki and with the approval of the local ethics committee of Charité University Medicine Berlin (Ethikkommission der Charité - Universitätsmedizin Berlin, Nr. EA2/162/19).

Baseline patient's characteristics were acquired at time of the first examination.

On the day of the measurements no training was performed. SWE investigation was performed on twenty-four athletes before and after a standardized running exercise. The running protocol was performed on a treadmill with 1% incline. The treadmill velocity was 6km/h at the start, and was increased by 2km/h every three minutes. The protocol lasted 18 to 21 minutes until individual exhaustion. After the treadmill exercise, SWE measurements were performed again to examine the stiffness of the lower limb. All measurements were jointly performed by a trained sonographer and a highly experienced radiologist and a sports medicine doctor.

Shear Wave Elastography protocol

All US-SWE examinations were performed using a standardized protocol. For assessment of the achilles tendon (mid portion), participants were examined in prone position with both feet hanging in relaxed position over the examination couch. Prior to US-SWE, gray-scale B-mode US was performed in transverse and longitudinal planes for adequate assessment of tendons and probe position. All examinations were performed using a high-end US system with a 4-10 MHz multifrequency linear array transducer and a center frequency of 7 Mhz (Acuson Sequoia, Siemens Healthineers, Erlangen, Germany). The US-SWE software (Virtual Touch™) allows real-time measurement using Acoustic Radiation Force Impulse (ARFI) imaging technology for quantitative evaluation of shear wave speed.

US examinations were performed in the longitudinal plane to depict each tendon and the area of interest in one single image. Using the respective 2D SWE approach, the examiner acquired four US images of each tendon and muscle of both legs with consecutive SWE measurements using a 3-mm circular region of interest (ROI) placed in the center of each target tendon avoiding areas of visible artifacts. Thus, representative tendon stiffness is given as the median of 12 measurements and corresponding IQR. Before ROI placement, SWS was depicted by color-coded SWE mapping. The standardized penetration depth was adapted to each participant for optimal visualization of the tendon and correct SWE measurement. Gain was not changed to avoid potential effects on US-SWE measurements.

Statistical analysis

Continuous variables were tested for normal distribution using the Kolmogorov-Smirnov test. Not normally distributed variables are reported as median and interquartile range (IQR). Categorical variables were compared using Student's t-test or the chi² test, as appropriate, and reported by their proportion (n/N), as absolute values and in percent.

A two-sided significance level of α = 0.01 was defined appropriate to indicate statistical significance. All statistical analyses were performed using the SPSS software (IBM Corp., released 2019. IBM SPSS Statistics for Windows, Version 26.0. Armonk, NY: IBM Corp.).

Results

Athletes` characteristics

A total of 24 female professional athletes with a median age of 27.7 were examined. The median body mass index (BMI) was 23.17kg/m2 (IQR, 19.6-32.2). One athlete had been diagnosed with hypothyreosis, while no other diseases as diabetes, fatigue, hyperlipidemia, rheumatic diseases or malposition of lower limb joints were reported. Overall, eleven atheletes reported rupture of lower ligaments (ligament rupture of the ankle [n=8), ligament rupture knee [n=7]). None reported a tendon rupture. Currently taken medication were L-Tyroxin (n=1) and hormonal contraceptives (oral [n=4],   intrauterine device [n=2]).

All measurements were performed in professional athletes of the volleyball national team (n=13) or the German handball league (n=11). 84% of all athletes trained more than 10 hours per week, 16% trained 5-10 hours per week.

Results of US-SWE examination

There was no difference in tendon and muscle SWS between type of sport (volleyball [AT 11.11m/s; MS 1.75m/s; MGC 1.70m/s] and handball [AT 11.62m/s; MS 1.8m/s; MGC 1.76m/s]; p>0.05).

As visualized in Figure 1, no significant change in median SWS could be observed between intra-individual pre- and post-exercise measurements (values presented in Table 1s [supplement material]).

In the overall cohort, baseline SWE assessment demonstrated a moderate to strong correlation between pre-exercise and post-exercise stiffness for MS (r=0.613), MG (r=0.609) and AT (r=0.583). In both muscles and tendon, the linear regression shows an increase in stiffness for lower pre-exercise values and decreasing stiffness for higher pre-exercise values (Figure 2 and 3). This covariance between pre-exercise values and changes in stiffness and is highly significant (p < 0.001 for MS, MG and AT, cf. Table 1).

Table 1

Covariance between pre-exercise SWS and the SWS change towards post-exercise.

Estimation	MS	p-value	MG	p-value	AT	p-value
Intercept	1.5540	<0.001	1.0682	<0.001	6.8831	<0.001
SWV pre-exercise (m/s)	-0.9045	<0.001	-0.6644	<0.001	-0.6149	<0.001

Pre-exercise values and changes in stiffness showed a significant covariance using the ANOVA test

Abbreviations: SWS denotes shear wave speed; MS, Soleus muscle; MG, gastrocnemius muscle; AT, achill tendon.

Representative images of the change in tendon stiffness are shown in Figure 4.

Discussion

There is a lack of evidence if SWE is sensitive to tissue changes of the lower limb after a single training session in professional athletes. The aim of this study was therefore to examine the impact of an acute exercise on muscles and tendons, measured by SWE. While the median shear wave velocity did not differ between pre- and post-exercise, we detected an increase in stiffness for lower pre-exercise values and decreasing stiffness for higher pre-exercise values in professional female athletes.

For assessing SWE measurement, it is necessary to stick to a standardized measurement protocol, joints, tendons and muscles needed to be in a relaxed position and transducer positioning should be performed without pressure, thus joint position, contraction and pressure do have an impact on SWS (14). Regarding these influences, SWE is a reliable technique in assessing muscle and tendon stiffness (15).

However, exercise activity prior to the measurement can affect the results as indicated by an increase in stiffness for lower pre-exercise shear wave velocity values and decreasing stiffness for higher pre-exercise values in healthy tendons. This implies an individual response of healthy tendons and muscles to a mean optimal stiffness after a short training session in professional athletes. These individual changes post exercise should be considered when diagnosing tendon injuries. Transient changes in stiffness after heel drop exercises have been reported, however in non-professional participants (16). Decreased tendon stiffness was detected after long distance running (17). Risch et al. reported a higher intratendinous bloodflow in AT shortly after a treadmill running exercise in recreational and semiprofessional athletes in some participants, while other ATs were unaffected (18). In this study, especially stiffer ATs showed decreased stiffness values after acute exercise, which could be a sign of higher intratendinous bloodflow. The missing change of tendon stiffness in our cohort may be driven by a professional sports collective with a general high amount of training hours and ongoing stretching exercises combined with physiotherapy care. This study did not detect a stiffness difference between volleyball and handball players. This may be due to the similar training load and similar kinds of exercise activities such as running and jumping.

Professional female athletes seem to have a common AT stiffness after acute exercise between 11 m/s and 12 m/s. Although cut-off values are only useful for one ultrasound system, the general knowledge of changes in tendon stiffness regarding professional athletes is highly important for future research and potential prospective studies. Reference values and stiffness changes shortly after exercise needed to be considered while using SWE in preventive and rehabilitation medicine.

Overall, studies show that SWE is a suitable diagnostic tool for assessing the stiffness of tendons and muscles with potential applicationin rehabilitation and preventive medicine (19-21). Individual regular assessment of tissue health by SWE in professional sports could detect decreasing stiffness of achilles tendon, which may be associated with increased risk of injury. At once, in patellar tendon, with significant lower baseline SWS in comparison to AT, increasing stiffness was reported to correlate with tendinopathy (22). Thus, intra-individual changes of tendon stiffness measured by SWE provides additional information and could be implemented as a screening tool during long-term training plans or high-volume training camps to prevent injuries.

Dirrichs et al. examined that SWE provided good results for differentiating between subjects with painful tendinopathies and asymptomatic, healthy control subjects (10). The results were consistent with the VISA-A Score in subjects with achilles tendinopathy (23). SWE can be used to detect differences in sportive active and non-active individuals (12). When assessing stiffness values measured by SWE effects of gender needed to be considered (24, 25). While the effect of age on tendon stiffness, measured by SWE, is currently inconclusive (25-28).

Standardized SWE measurement protocols with precisely localized transducer positions and exactly defined positions of the test subjects during the measurement would further increase comparability of SWE data in MSK-studies (29). More precise and comparable research protocols in MSK-SWE could allow a great benefit in sports medicine but also in rehabilitation and preventive medicine (6, 10, 30-32).

Conclusion

Shear wave elastography may be applied to point out pathological changes, as changed stiffness values correlated with restricted mobility or pain. The technique of SWE could be used to define intra-individual threshold values for estimating the risk of injury individually. Especially for athletes, easy access diagnostics are necessary to detect early stages of injuries and to develop preventive therapy algorithms to avoid difficult to treat tendon and muscle injuries. In this context further studies are still necessary, as well as further standardization of the measurement method of SWE.

Declarations

Conflicts of interest:

Claudia Römer reports no conflicts of interests.

Kirsten Legerlotz reports no conflict of interests.

Julia Czupajllo reports no conflicts of interests.

Thomas Fischer reports having received consultancy honoraria from Bracco, Canon Medical Imaging and Siemens Healthineers.

Bernd Wolfarth reports no conflicts of interest.

Markus H. Lerchbaumer reports having received consultancy honoraria from Canon Medical Imaging.

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Authors' Contributions

CR, TF and MHL conceived of the presented idea. CR, JC and MHL enrolled patients and performed imaging. CR and MHL performed the data analysis and drafted the manuscript. All authors revised the manuscript critically for important intellectual content and approved the final manuscript.

Data availability:

The datasets generated and analysed during the current study are not publicly available due internal data protection regulation but information is available from the corresponding author on reasonable request.

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Figures

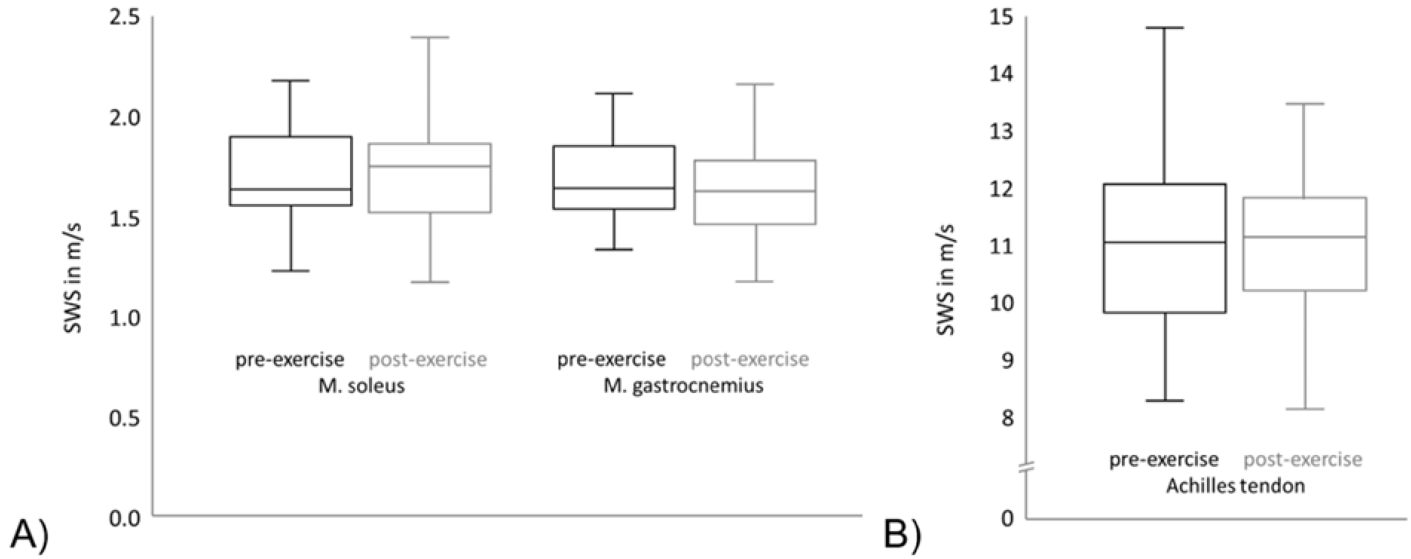

Figure 1

Shear wave speed (SWS) of pre- and post- exercise measurements for A) the Achilles tendon and B) the soleus and gastrocnemius muscle

Both muscle (a) and tendon stiffness (a) showed no significant change prior and after standardized treadmill exercise

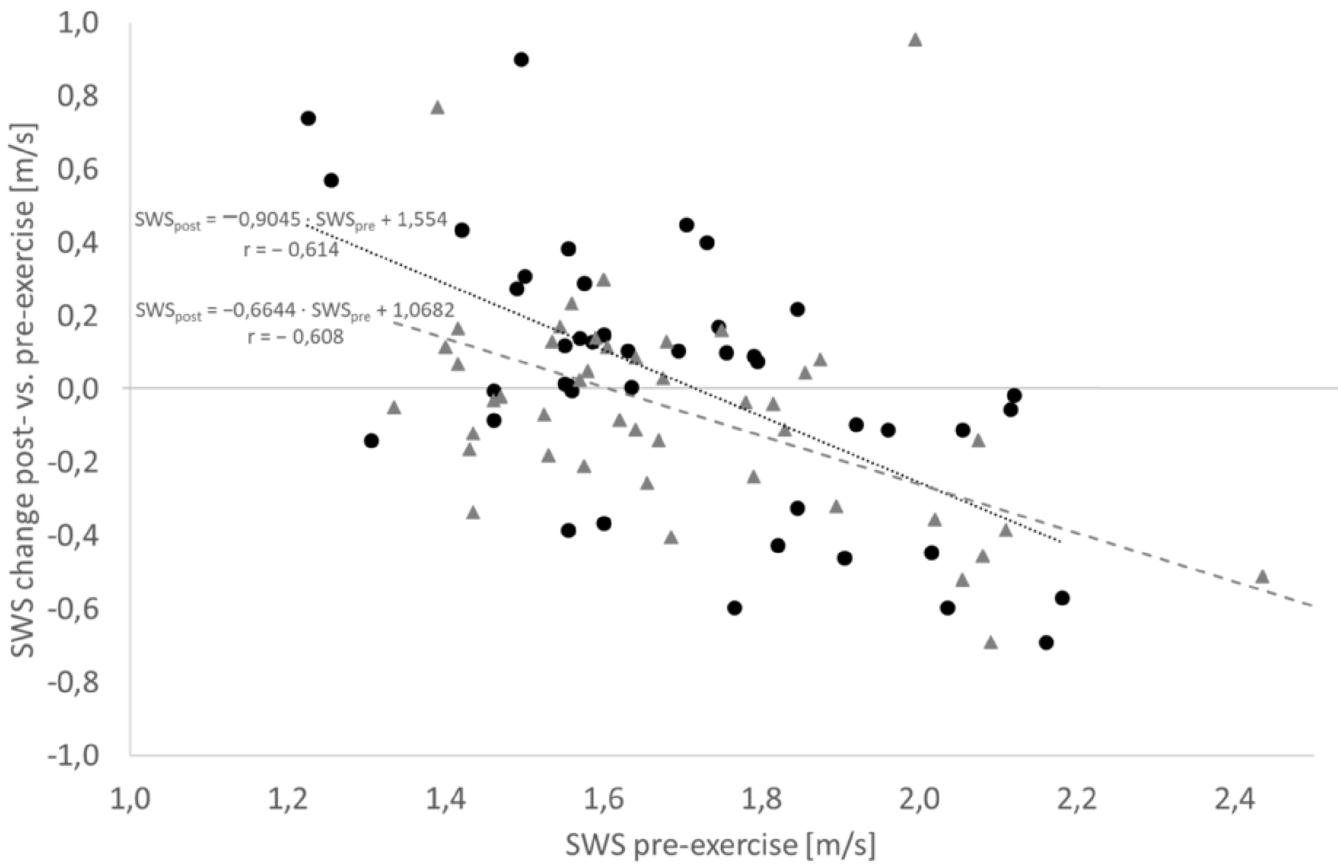

Figure 2

Linear regression of shear wave speed (SWS) change post- vs pre- exercise measurements in comparison with pre-exercise SWS (x=SWS in m/s; y=delta (SWS_{post}-SWS_{pre}) for Soleus muscle (circle) and Gastrocnemius muscle (triangle)

The linear regression shows an increase in stiffness for lower pre-exercise values and decreasing stiffness for higher pre-exercise values for Soleus and Gastrocnemius muscle. This covariance between pre-exercise values and changes in stiffness is highly significant ($p < 0.001$ for MS and MG).

For both MS and MG the respective regression models are given in Figure 2. In particular for MS (circle) the slope of -0,9045 indicates an almost complete compensation of pre-exercise SWS towards post-exercise SWS. Both models intersect with the horizontal zero SWS change straight between 1,6 and 1,7 m/s pre-exercise SWS and are similar to the distribution’s mean values.

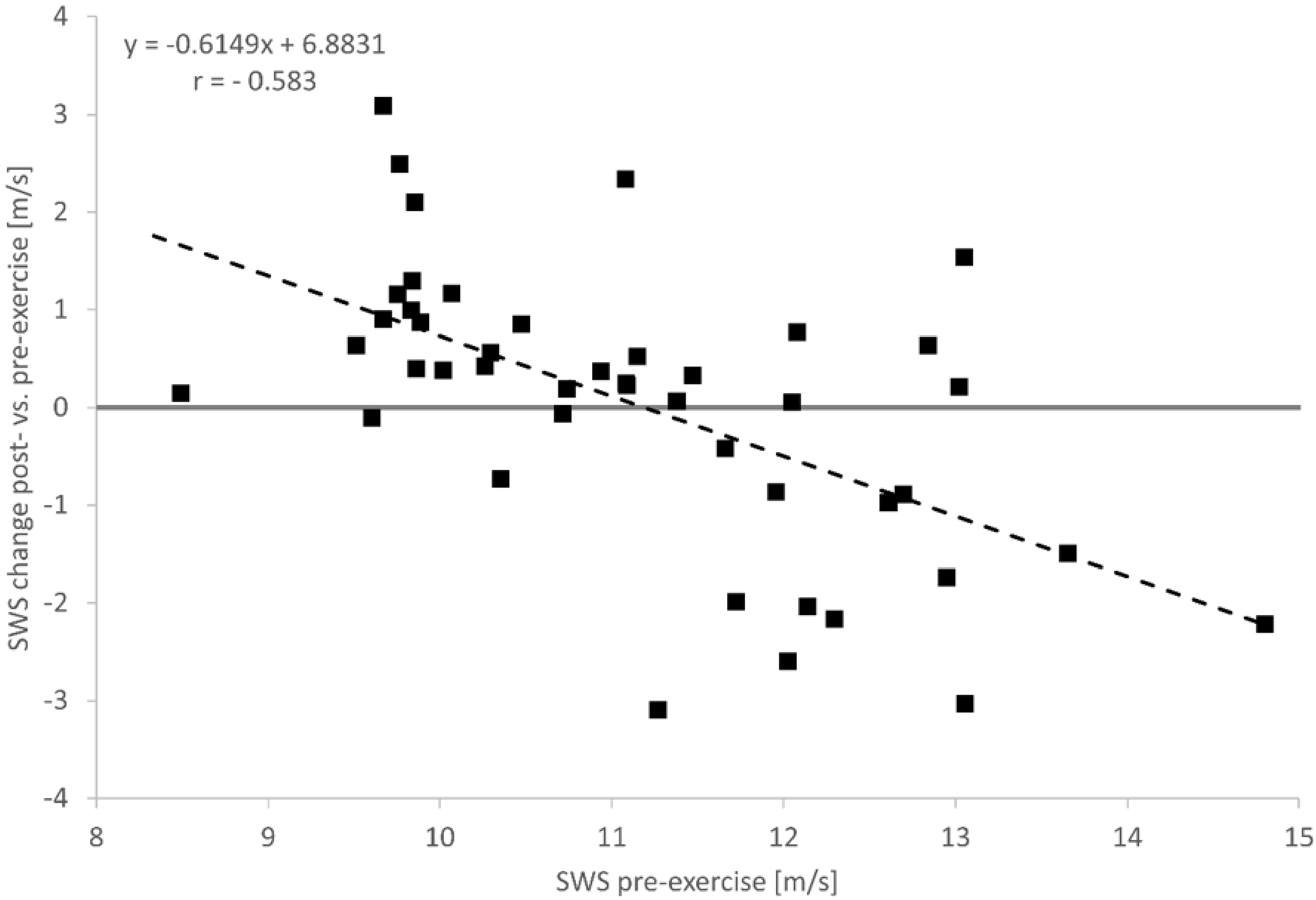

Figure 3

Linear regression of shear wave speed (SWS) change post- vs. pre-exercise measurements in comparison with pre-exercise (x=SWS in m/s; y=delta (SWS_{post}-SWS_{pre}) for Achilles tendon

The linear regression shows an increase in stiffness for lower pre-exercise values and decreasing stiffness for higher pre-exercise values for Achilles tendon. This covariance between pre-exercise values and changes in stiffness is highly significant ($p < 0.001$ for AT).

The regression model's slope and intersect values for AT are also given in Figure 3. Again, the model's intercept with the horizontal zero SWS change straight at 11,2 m/s is similar to the SWS pre-exercise median value of 11.08 m/s for AT.

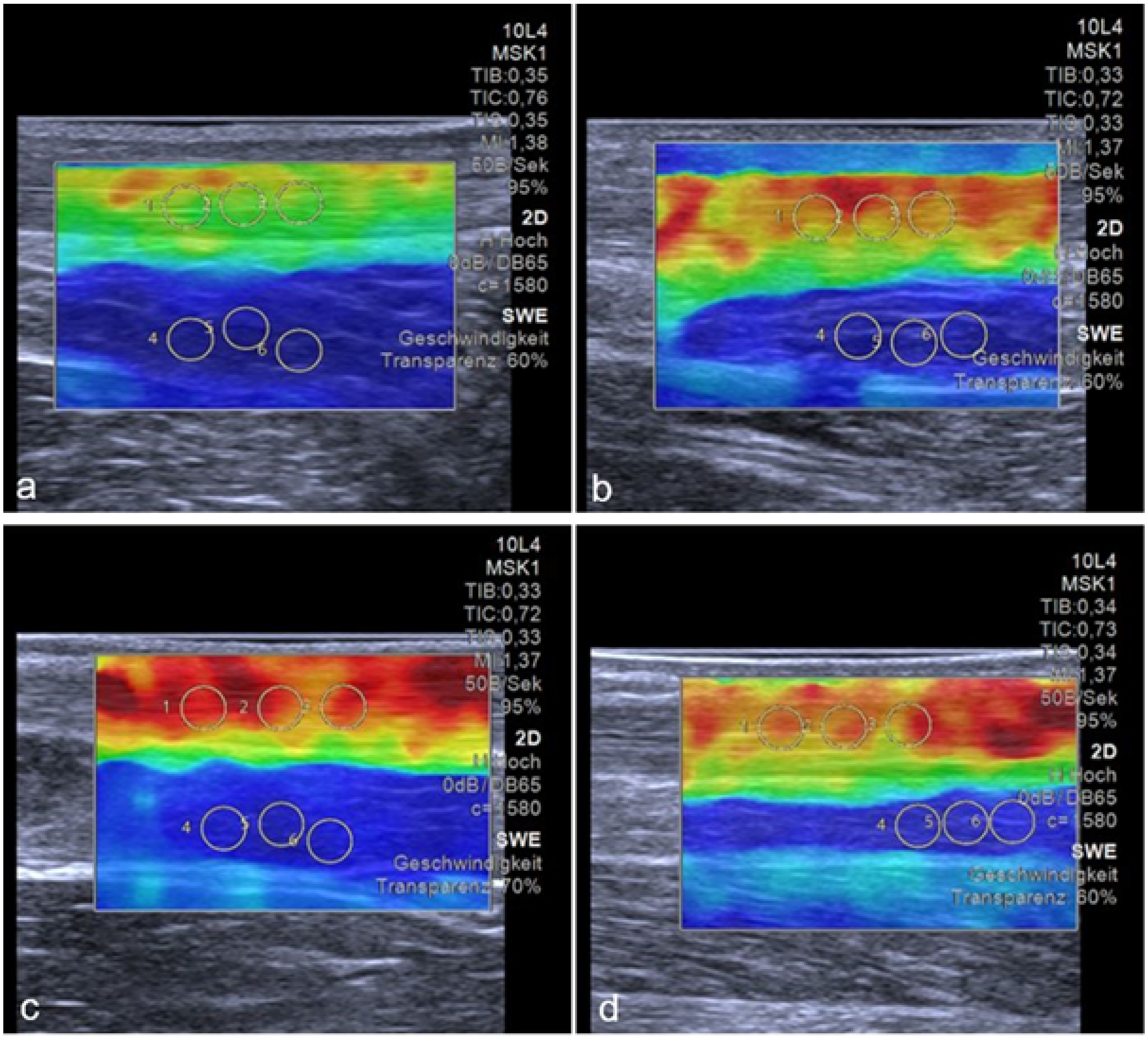

Figure 4

Representative SWE images of a two professional female athletes prior and after standardized treadmill exercise

Color-coded SWE maps presenting the AT stiffness of two athletes. On 2D-SWE color maps, red is coded as hard tissue and blue as soft. The overall shear wave speed was calculated by four images with three regions per structure, given an overall number of 12 measurements per tendon or muscle. In this figure, a female athlete with lower baseline SWS (a) showed an increase of stiffness after exercise (b), while another athlete with higher baseline stiffness (c) showed a slightly reduction of SWS (d). (Gastrocnemius muscle not shown in this images)

Abbreviation: AT denotes achill tendon; SWE, shear wave elastography; SWS, shear wave speed.

Supplementary Files

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- SWEtreadmillSupplementmaterial.docx